THE SELECTIVITY OF COAL MINERALS AND SRC RESIDUE

ASHES FOR HYDRODESULFURIZATION IN THE SRC PROCESS

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INTRODUCTION

Many improvements have been made in the Solvent Refined Coal (SRC) process over the past year. During this time period, several solid/liquid separation techniques have evolved that offer promise for cost reduction in ash removal. Concurrently, technical feasibility for the Kerr-McGee's process for critical solvent deashing has been demonstrated on a pilot scale at the Wilsonville SRC facility. Since this separation process can be used to fractionate liquified coal as well as for deashing, a fraction of the liquefied coal could be used as make-up process solvent. As a result, process solvent regeneration appears no longer to be a limiting operational factor for the dissolver stage (1). Now the dissolver performs three basic functions: liquefaction of coal, regeneration of the process solvent and desulfurization of coal liquids. Several studies have shown that liquefaction occurs very rapidly while desulfurization occurs slowly. Thus, now that the Kerr-McGee's process can be used to offset solvent deficiencies, desulfurization may limit dissolver operations, particularly when a solid SRC is produced.

Hydrogen generation for SRC processing is a major operational cost, making short reaction times with minimum hydrogenation severity desirable. The overall objective of this study is to develop a methodology for using mineral additives to increase the rate of desulfurization during coal liquefaction. Some iron containing minerals, including the ash of SRC residue, have been shown to act as in situ sulfur scavengers (2). The addition of such minerals to the dissolver feed may allow sulfur removal requirements to be met with shorter reaction times and consequent lower hydrogen consumption.

The role of mineral additives in coal liquefaction processing is to increase desulfurization with minimal but sufficient hydrogenation. Selectivity is a measure used to rate the effectiveness of the different mineral additives studied. By definition, selectivity is the ratio of the amount of sulfur removal to the amount of hydrogen consumed for a given reaction time.

In previous studies, the effects of relatively large amounts of mineral additives on reaction rates have been examined (3) in order to clearly delineate the effects of the additives. However, in actual application, such large amounts would be prohibitive due to the associated material handling difficulties. Therefore, one of the major objectives of this work is to demonstrate that only small, easily processed, amounts of mineral additives are required for effective sulfur scavenging, provided that the iron contained in the additives is in a form available for reaction and is present in stoichiometric amounts.

EXPERIMENTAL

Reagents and Materials
Light recycle oil (LRO) and Western Kentucky 9/14 coal were obtained from the Wilsonville SRC Pilot Plant, operated by Southern Services, Inc. The LRO contains

0.2 % sulfur and the Western Kentucky coal is analyzed to be 67.8% C, 4.9%H, 3.10%S and 12% mineral matter. The coal was dried overnight at 100°C and 25 inches Hg vacuum before use.

Coal minerals, SRC residue ash; magnetite; pyrite; hematite; reagent grade Fe_2O_3; commercial Fe_2O_3 catalyst; and reagent-grade reduced iron,were used as mineral additives for hydrogenation and hydrodesulfurization reactions. Commercial grade Fe_2O_3 (Fe-0301T, 20% Fe_2O_3 mounted on activated alumina) was obtained from the Harshaw Chemical Company. This catalyst was ground to various particle sizes to study the effect of mass transfer on the reactions. Hematite was obtained from Cities Services and magnetite, from Chemialloy Chemical Company. SRC residue obtained from the Wilsonville SRC Pilot Plant was oxidized before use. Hydrogen gas of 99.995% purity was obtained from Union Carbide. All other chemicals were reagent grade.

Equipment
A small tubing bomb reactor and a commercial 300 cc magnedrive autoclave (Autoclave Engineers) were used for all reaction studies and have been previously described (2-4). Varian gas chromatographs (Models 1800 and 920) were used for analysis of liquid and gas liquefaction products. The sulfur content of coal and liquefaction products was determined by using a Leco Sulfur Analyzer (Model 532). Elemental analyses of various mineral additives were determined by energy dispersive X-ray fluorescence analysis (EDXRF). The surface area of the mineral additives was determined by the nitrogen adsorption technique.

Reaction Conditions:
Coal liquefaction reactions were performed for time periods ranging from 15 to 120 minutes, at 410°C and with stirring rates of 1000 rpm except during mass transfer studies when the reactions were stirred at different rates ranging from 600 to 1400 rpm. The autoclaves were charged with 40g of coal, 80g of LRO, and 10g of additive. Benzothiophene desulfurization was studied in a small tubing bomb reactor (12ml capacity). The benzothiophene reaction, 10% benzothiophene in dodecane with appropriate amounts of mineral additives, was performed at 1250 psi hydrogen pressure (at room temperature) and 410°C for 30 minutes.

RESULTS AND DISCUSSION

Effect of the Amount of Additive
Elemental iron has been shown to act as an effective in situ sulfur scavenger (2-4). The effect of different amounts of iron on the sulfur content of the total liquid products from coal liquefaction reactions is shown in Figure 1 where the ratio S/S_B is plotted versus Fe/Fe_S. These ratio terms are defined as: S is the weight percent of the residual sulfur; S_B, residual sulfur for the baseline case, i.e. no iron present for the same reaction conditions; Fe, the weight percent of iron added; Fe_S, the stoichiometric amount of iron required to react with the sulfur to be removed. Fe_S is computed on the following basis: 1) the organic sulfur content of the coal is 1.23%; 2) pyritic sulfur of the coal, 0.79%, is reduced to the FeS form; and 3) the sulfur content of the solvent is 0.27%. The residual sulfur (S/S_B) decreased significantly (from 0.79 to 0.53) with increasing amounts of iron (Fe/Fe_S = 1.3 to 20). The decrease in residual sulfur content is most significant when Fe/Fe_S is less than 10. When Fe/Fe_S is increased from 10 to 20, a decrease of only 0.07 occurred in S/S_B which is just slightly more than the standard deviation of S/S_B ($\pm$ 0.02). Therefore, in this range, additional amounts of iron appear to have little effect on sulfur removal.

The effect of different amounts of Fe_2O_3 on residual sulfur is also shown in Figure 1. No significant decrease in residual sulfur occurs, when 71% of the stoichiometric required amount of iron is present as Fe_2O_3 (i.e. Fe/Fe_S = 0.71).

It should be noted that the surface area of the Fe_2O_3 used in this study is 8.9 m^2/gm. (Table I) Apparently, since no hydrogen sulfide (H_2S) is present in the product gases when stoichiometric amounts of iron are present, all of the iron present in the form of relatively high surface Fe_2O_3 reacts with any H_2S formed. Furthermore, essentially the same degree of desulfurization occurs with a stoichiometric excess of Harshaw iron catalyst, which has a surface area of 60 m^2/gm, as that obtained with an equivalent amount of Fe_2O_3. Therefore, the greater surface area of the Harshaw catalyst does not appear to have any significant effect on desulfurization, because equivalent amounts of iron are available in both cases to react with the H_2S produced in the reactor.

The effect of different amounts of iron and Fe_2O_3 on the final hydrogen partial pressure and, consequently, on total hydrogen consumption is shown in Figure 2. The same amount of hydrogen is consumed in either the presence or absence of iron: H_f/H_o = 0.58 $\pm$ 0.02, where H_f and H_o are the final and initial hydrogen partial pressures, respectively. Under the same reaction conditions, more hydrogen is consumed when Fe_2O_3 is present: H_f/H_o = 0.45 $\pm$ 0.01; however, approximately the same amount of hydrogen is consumed irrespective of the amount of Fe_2O_3 present. Since hydrogen consumption does not depend on the quantity of Fe_2O_3 present, Fe_2O_3 is not significantly reduced at the reaction conditions used. Since more hydrogen is consumed with Fe_2O_3, the selectivity of iron (sulfur removal per hydrogen consumption) is higher than that of Fe_2O_3, provided that sufficient iron, i.e. Fe/Fe_S=10, is present (Fig. 3).

Model Compound Studies

The hydrogenation of benzothiophene under different reaction conditions and with different catalysts produces a variety of products including ethylbenzene, dihydrobenzothiophene, styrene and phenylethanethiols (5,6). Using the iron additives listed in Table I and the reaction conditions stated, the major products observed in this study are ethylbenzene and dihydrobenzothiophene.
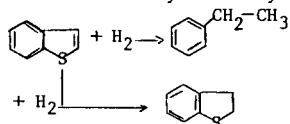
The conversion of benzothiophene to these reaction products as catalyzed by the different mineral additives is given in Table 1. The mineral additives, Fe_2O_3 and Co-Mo-Al, promoted complete conversion of benzothiophene to ethylbenzene. However, complete conversion to ethylbenzene does not result when iron is the mineral additive; in fact, only 45% of the benzothiophene is converted to ethylbenzene with no significant dihydrobenzothiophene formation. In the benzothiophene reaction, the amount of iron used is considerably less than the amount found necessary for maximum desulfurization of coal/oil reaction mixtures. The Fe/Fe_S for the benzothiophene reaction is 2.7 compared to the optimum Fe/Fe_S of 10 observed for the coal/oil slurries. While in the range of Fe/Fe_S < 10, desulfurization has been shown in the coal/oil reactions to depend on the amount of iron present. This result is verified in the benzothiophene reaction as given in Table II, where the conversion of benzothiophene is shown to vary significantly with the amount of iron present during the reaction. The conversion of the benzothiophene increaes from 23 % to 54% with a corresponding increase of Fe/Fe_S from 0.72 to 2.7. Furthermore, when a Harshaw catalyst is used and iron is present in the amount of Fe/Fe_S = 0.37, a low conversion of benzothiophene is observed; whereas, complete conversion to ethylbenzene occurs when approximately twice the required stoichiometric amount, Fe/Fe_S = 1.9, is used. As observed in the coal/oil reactions discussed previously, the higher surface area Harshaw Fe_2O_3 catalyst does not result in any significant increases in the desulfurization of the benzothiophene system.

Iron sulfide additives, pyrite and FeS_{1+x}, do not react with the H_2S product, and, as previously reported (3,4), are not as effective in increasing desulfurization

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rates as iron and Fe_2O_3. The results given in Table II concur with these conclusions. In the presence of the iron sulfide additives, the benzothiophene is converted primarily to dihydrobenzothiophene -- a product of hydrogenation -- instead of ethylbenzene -- a product of hydrodesulfurization. In contrast, when iron or Fe_2O_3 is present during reaction, the primary product is ethylbenzene.

Effect of Reaction Time

The rate of hydrodesulfurization of coal liquids is generally consistent with that of petroleum feedstocks: both substances are considered mixtures of sulfur-containing compounds, each of which reacts at a rate proportional to its concentration. The rate of the total sulfur removal can be approximated as if there are only two reactive components.

$$r_{HDS} = \alpha_1 \ K_1 \ C_S + \alpha_2 \ K_2 \ C_S$$

where C_S is the total concentration of the sulfur-containing compounds; α_1 and α_2 are the fractions of reactive and unreactive components, respectively; K_1 and K_2 are the rate constants of the reactive and unreactive components (7).

The parameters, α_1, α_2 and K_1, K_2, vary according to the additive present during reaction as shown in Figure 4. When Fe_2O_3 is added, more sulfur is removed in the first 15 minutes of reaction than in two hours when no additive is present. In addition, considerably less hydrogen is consumed when Fe_2O_3 is present in a 15 minute reaction than after two hours without any additives (See Figure 5). The hydrogen consumption with Fe_2O_3 is 20% as opposed to 44% for no additive. The use of mineral additives such as Fe_2O_3 is beneficial, in that shorter reaction times are needed for desulfurization with less total hydrogen consumption. Furthermore, these minerals can be added without any sacrifice in coal conversion as shown in Figure 6.

Influence of Mass Transfer

The three phase reaction system present in coal liquefaction may be influenced by mass transfer effects. To determine whether mass transfer regulation is occurring, experiments were performed using different stirring rates and different particle sizes.

A direct test to determine the importance of gas/liquid transport was performed by varying the stirring rates while holding all other variables constant. As can be seen in Table 3, for stirring rates between 660 and 1460 rpm, neither the rate of desulfurization nor hydrogen consumption is very sensitive to and, consequently, is not affected by agitation rate. Therefore, gas/liquid mass transport has no apparent influence on either hydrogenation or desulfurization.

Generally, decreasing the catalyst particle size increases the effectiveness factor and the liquid/solid mass transfer coefficient. Reducing the particle size will increase the observed reaction rate when the reaction is controlled either by liquid/solid mass transport or by pore diffusion. However, reducing the particle size is not a definitive test for pore diffusion. Although the behavior of Fe_2O_3 is more like a reactant than a catalyst, the absence of particle size effects should be indicative of the absence of liquid/solid mass transfer control.

A series of experiments were performed with different Fe_2O_3 particle sizes to determine the effect of particle size on desulfurization. The rate of desulfurization is observed to be essentially independent of particle size as shown in Table IV. The rate of hydrogen consumption does vary slightly with different particle sizes.

Since the observed desulfurization rate is independent of both the Fe_2O_3 particle size and the stirring rate (within experimental error), it appears that

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desulfurization is neither pore diffusion nor liquid/solid mass transfer controlled, implying then that the reaction is kinetically controlled. The rate of hydrogen consumption may be somewhat limited by mass transfer since it is influenced by particle size. An indication of the importance of particle size on hydrogen consumption rate is demonstrated in Table V. The rate of hydrogenation increases with decreasing particle size.

Comparison of Activities of Different Coal Mineral Additives

Coal mineral residues from the SRC process and ashes from the residues and Western Kentucky 9/14 coal were added to the coal liquefaction reactions to determine their effect on desulfurization and hydrogen consumption. An elemental analysis of the additives is given in Table VI. The iron content of these additives ranges from a low of 3.37% in SRC residue to a high of 26.92% in Western Kentucky ash while the sulfur content ranges from 0.47% in SRC ash to 3.81% in Kerr-McGee residue. The apparent differences in the elemental composition of SRC residue and Kerr-McGee residue observed in Table VI may be accounted for when the source of each is considered: SRC residue is obtained from filtration and Kerr-McGee residue is obtained through solvent deashing. In both cases, the residues were ashed to eliminate the carbonaceous coating and to convert the minerals to an oxide form for sulfur scavenging.

A comparison of the activity of different coal mineral additives is given in Table VII. In the cases of no additive, SRC residue, and Kerr-McGee residue, the organic sulfur removed from the system is essentially identical. The same is true for hydrogen consumption. After ashing, both the Kerr-McGee and SRC residue ashes show increased activity for sulfur removal; from ∿ 23% for the residue to 43% for the ashes. Two possible reasons for these differences are: 1) the carbonaceous coating may not completely dissolve under reaction conditions, in effect, inhibiting sulfur scavenging or 2) the change in mineral form upon oxidation may provide the correct form for sulfur scavenging. Although the iron concentration in the Kerr-McGee residue ash is approximately three times higher than that of the SRC residue ash, the sulfur removal is essentially the same. This fact may be due to the difference in coal type, the mineral forms in the coal feedstock and the mineral forms present after processing and ashing. Mineral inhibitors may also be present in the Kerr-McGee residue ash that limit sulfur removal. Another possible reason for the same sulfur removal even with different iron contents for the two ashes is that the sulfur content of the Kerr-McGee residue ash is greater than that of the SRC residue ash.

The activity of iron, magnetite (Fe_3O_4) and Fe_2O_3 is compared in Table VIII. Fe_2O_3 and Fe show essentially the same amount of sulfur removal although their surface areas differ by more than an order of magnitude. In contrast, magnetite has a surface area between that of Fe and Fe_2O_3 but does not have the ability to remove sulfur like Fe_2O_3. It appears from Table VIII that magnetite is not as effective as a sulfur scavenger as Fe; however, since equivalent amounts of iron, Fe/Fe_S, are not used and sulfur removal is sensitive to the amount of iron present when $Fe/Fe_S < 10$, more experimental data is needed to compare their relative activities. Both magnetite and Fe have a low surface area and low hydrogen consumption while Fe_2O_3 has a relatively high surface area and a much higher hydrogen consumption. Since hydrogenation appears to be somewhat limited by mass transfer, the differences in selectivity among Fe, magnetite and Fe_2O_3 may be due to the effects of mass transfer.

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Table I: EFFECT OF MINERAL ADDITIVES ON THE HYDRODESULFURIZATION OF BENZOTHIOPHENE

ADDITIVE	Fe/Fe_s	BENZOTHIOPHENE CONVERSION,%	PRODUCT DISTRIBUTION OF CONVERTED BENZOTHIOPHENE,%		
			DIHYDROBEN-ZOTHIOPHENE	ETHYL-BENZENE	HYDRODESULFUR-IZATION,%
NONE	—	0.0	0.0	0.0	0.0
CO-MO-AL	—	100.0	0.0	100.0	100.0
Fe_2O_3 (Reagent grade)	1.9	100.0	0.0	100.0	100.0
Fe	2.7	45.0	5.0	95.0	43.0
Reduced Pyrite, FeS_{1+X}	—	42.0	65.0	35.0	15.0
Pyrite, FeS_2	1.2	40.0	90.0	10.0	8.0

Benzothiophene: 0.45g
Additive: 0.5g

Table II: EFFECT OF Fe AND Fe_2O_3 ON HYDRODESULFURIZATION OF BENZOTHIOPHENE

ADDITIVE	Fe/Fe_s	BENZOTHIOPHENE CONVERSION,%	PRODUCT DISTRIBUTION OF CONVERTED BENZOTHIOPHENE,%		
			DIHYDROBEN-ZOTHIOPHENE	ETHYL-BENZENE	HYDRODESULFUR-IZATION,%
NONE	—	0.0	0.0	0.0	0.0
Fe(3%)	0.72	23.0	39.0	61.0	14.0
Fe(6%)	1.4	35.0	26.0	74.0	26.0
Fe(10%)	2.7	54±2.0	0.0	100.0	54±2.0
HARSHAW Fe_2O_3 (10%)	0.37	24.0	40.0	60.0	13.0
POWDER Fe_2O_3 (10%)	1.9	100.0	0.0	100.0	100.0

Benzothiophene: 0.45g
Additive: 0.5g

Table III: EFFECT OF AGITATION RATE ON COAL LIQUEFACTION USING A HARSHAW IRON CATALYST

RPM	H_2S PARTIAL PRESSURE, psig	SULFUR[a] DISTRIBUTION, %		YIELD[b] H_f/H_o %	HYDROGEN[c] CONSUMPTION, %	SULFUR[d] REMOVAL, %	DESULFURIZATION RATE, % SULFUR REMOVAL MIN.	HYDROGEN CONSUMPTION RATE, % HYD. CONS. MIN.
		TOTAL LIQUID	SRC					
600[e]	0.0	0.26	0.58	87.0 0.38	62.0	56.0	0.467	0.517
800	0.0	0.25	0.56	87.0 0.37	63.0	58.7	0.489	0.525
1000	0.0	0.29	0.65	90.0 0.34	66.0	51.7	0.431	0.55
1400	0.0	0.28	0.57	90.0 0.42	58.0	53.3	0.444	0.483

Reaction Time: 120 minutes   Initial Hydrogen Pressure: 2000 psi   Additive: 10g

aS_o = 0.60% Organic Sulfur Content of the Coal Oil Slurry

bYield,% = $\dfrac{Ash_f - Ash_{in}}{Ash_f(1 - Ash_{in})} \times 100$

cHYDROGEN CONSUMPTION,% = $1 - \dfrac{H_f}{H_o} \times 100$ (This is % of hydrogen charged initially into the reactor.)

dSULFUR REMOVAL,% = $\dfrac{S_o - \text{Total Liquid Sulfur}}{S_o} \times 100$

eStirring rates below 600 are impractical due to solid settling problems.

Table IV: EFFECT OF Fe_2O_3 PARTICLE SIZE ON COAL LIQUEFACTION

PARTICLE SIZE, MESH	H_2S PARTIAL PRESSURE psig	SULFUR DISTRIBUTION, %		YIELD, H_f/H_o %	HYDROGEN CONSUMPTION, %	SULFUR REMOVAL %	DESULFURIZATION RATE, % SULFUR REMOVAL MIN.	HYDROGEN CONSUMPTION RATE, % HYD. CONS. MIN.
		TOTAL LIQUID	SRC					
-35+ 60	0.0	0.26	0.56	73.0 0.53	47.0	56.7	0.472	0.392*
-60+ 80	0.0	0.30	0.64	90.0 0.43	57.0	50.0	0.417	0.475
-80+150	0.0	0.26	0.54	89.0 0.50	50.0	56.7	0.472	0.417
-80+150	0.0	0.26	0.59	90.0 0.46	54.0	56.7	0.472	0.45
-200	0.0	0.29	0.65	90.0 0.34	66.0	51.7	0.431	0.55

*Lower hydrogen consumption because of incomplete coal dissolution (73.0% as opposed to 90.0%).

Reaction Time: 120 minutes
Fe_2O_3: 10g

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Table V: PORE-DIFFUSION STUDY

PARTICLE SIZE, MESH	AVERAGE SIZE, mm.	HYDROGEN CONSUMPTION RATE, %/MIN.
-35+ 60	0.335	0.392
-60+ 80	0.214	0.475
-80+150	0.141	0.417
-80+150	0.141	0.45
-200	0.0895	0.55

Table VI: X-RAY ANALYSES OF DIFFERENT COAL LIQUEFACTION RESIDUES AND THEIR ASHES

ELEMENT	SRC RESIDUE (KY 9/14 COAL)	SRC ASH (KY 9/14 COAL)	WEIGHT K-M RESIDUE (KY 6 COAL)	PERCENT K-M-ASH (KY 6 COAL)	KY 9/14 COAL ASH
Si	13.54	27.86	6.97	23.86	18.02
Fe	3.37	6.80	5.66	18.49	26.92
Ca	1.30	3.03	0.31	1.16	1.55
K	0.43	1.01	0.67	2.02	1.75
Cl	0.22	0.37	0.62	0.26	0.46
Ti	0.14	0.34	0.19	0.61	0.66
Mn	0.02	0.05	0.03	0.09	0.09
Sr	0.04	0.09	-	-	0.07
Zn	-	0.02	0.02	0.06	0.03
V	-	0.04	0.02	-	0.09
Cu	-	0.02	0.02	0.14	0.10
Br	-	-	-	-	-
Rb	-	-	-	-	0.01
Pb	-	-	-	-	-
Al	3.86	9.20	3.29	10.51	11.11
Mg	-	2.10	2.20	-	-
S	2.14	0.47	3.81	0.58	0.86
C	54.02	-	59.33	-	-
H	2.67	-	3.44	-	-
N	1.35	-	1.56	-	-
O(by difference)	16.90	51.40	11.86	42.22	38.28
	100.00	100.00	100.00	100.00	100.00
Surface Area m²/gm.	-	4.78±0.03	-	8.8±0.14	4.6±0.045

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Table VII: COMPARISON OF ACTIVITY OF DIFFERENT COAL MINERAL ADDITIVES

ADDITIVE	PARTIAL PRESSURE OF H_2S, psig	HYDROGEN CONSUMPTION, %	TOTAL LIQUID SULFUR, %	ORGANIC SULFUR REMOVAL %	Fe/Fe_s	Se	SURFACE AREA m^2/g
None	16.0	41.0	0.46	23	-	0.57	
SRC Residue	58.0	42.0	0.46	23	0.56	0.56	
SRC Ash	3.0	51.0	0.34	43	0.81	0.85	0.85
Kerr McGee Residue	14.0	46.3	0.47	22	0.98	0.47	
Kee McGee Ash	1.0	49.0	0.35	42	2.25	0.85	0.85
Western Ken. 9/14 Coal Ash	1.8	52.0	0.34	43	3.21	0.83	0.83

Average Coal Dissolution is 90.0% in all cases.
Reaction Time: 120 minutes
Additive: 10g

Table VIII: COMPARISON OF ACTIVITY OF Fe, MAGNETITE AND Fe_2O_3 (REAGENT GRADE)

ADDITIVE	PARTIAL PRESSURE OF H_2S, psig	HYDROGEN CONSUMPTION, %	TOTAL LIQUID SULFUR, %	ORGANIC SULFUR REMOVAL, %	Fe/Fe_s	SURFACE AREA m^2/gm.	Se
Fe_2O_3 (Reagent Grade)	0.0	55.0	0.25	55	6.86	8.9±0.04	1.0
Magnetite	0.0	43.6	0.35	41	8.83	0.75±0.02	0.94
Fe	0.0	41.5	0.28	53	10.42	0.25±0.01	1.3

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Figure 1

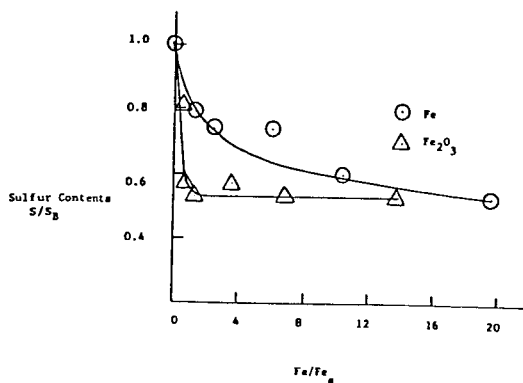THE EFFECT OF Fe AND Fe2O3 ON THE
SULFUR CONTENT OF THE
TOTAL LIQUID PRODUCTS

Figure 2

THE SELECTIVITY OF Fe AND Fe2O3
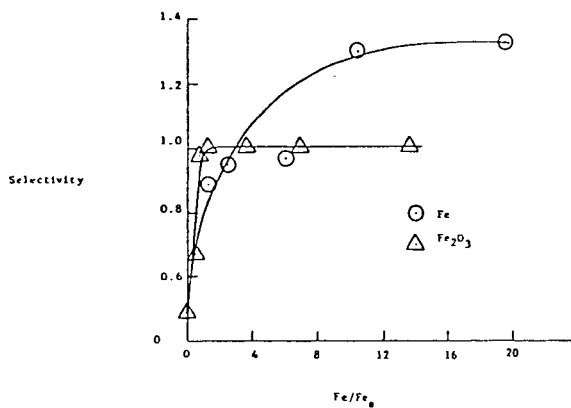FOR SULFUR REMOVAL ON THE BASIS OF EQUIVALENT AMOUNTS OF Fe

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Figure 3

THE EFFECT OF Fe AND Fe₂O₃ ON HYDROGEN
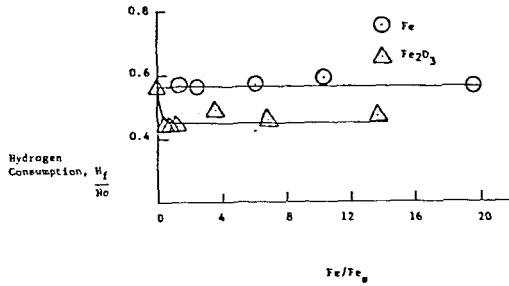CONSUMPTION AS A FUNCTION OF Fe CONCENTRATION

Figure 4

THE EFFECT OF ADDITIVE TYPE
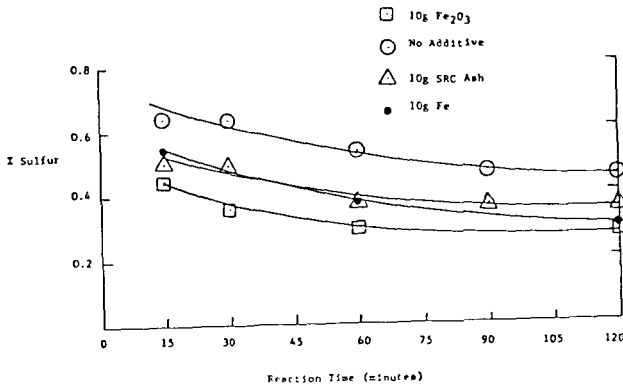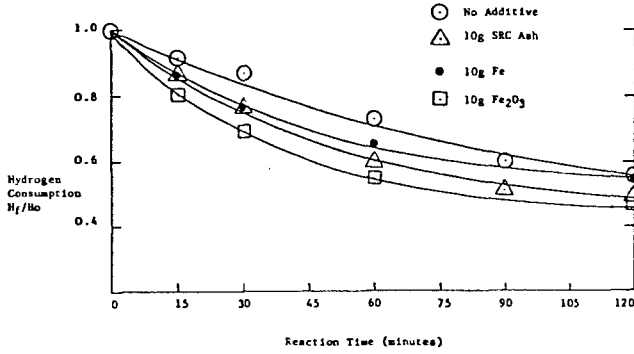ON SULFUR REMOVAL

Figure 5

THE EFFECT OF ADDITIVE TYPE
ON HYDROGEN CONSUMPTION

Figure 6

THE EFFECT OF ADDITIVE TYPE
ON COAL CONVERSION

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